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Report on Experimental Forest Treatments in the Flagstaff Urban/Wildland Interface

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REPORT ON EXPERIMENTAL FOREST TREATMENTS IN THE FLAGSTAFF URBAN/WILDLAND INTERFACE

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Executive Summary

This report describes the initial stages of an experiment to test forest treatments designed to restore natural ecological qualities and reduce the hazard to intense wildfires in the urban/wildland interface around Flagstaff, Arizona. The report is divided into two parts. In part one, we describe the pre-treatment conditions of the experimental blocks and the alteration in tree structure caused by thinning:

- Tree structure prior to the thinning treatment (composition, size distribution, biomass,snags),
- Tree structure after thinning,
- Tree biomass removed,
- Understory substrates before treatment (plants, litter, soil),
- Forest floor fuels before treatment.

In part two, we compared potential fire behavior under dry, windy weather conditions in the 12 ponderosa pine stands treated with alternative thinning prescriptions in this experiment. Before thinning, simulated fire behavior under the 97th percentile of June fire weather conditions was predicted to be intense but controllable (5.4 ft flame lengths). However, active or passive crownfires were simulated using crown base heights in the lowest quintile (20%) or winds gusting to 30 mph, representing the fuel ladders and wind gusts that are important for initiating crown burning. Under the identical conditions after thinning, all three treatments resisted crown burning.

Two research elements could not be included in this report. First, we cannot report post-treatment conditions because prescribed burning has not been completed to date in two of the three experimental blocks. We have worked closely with the Coconino National Forest, Grand Canyon Forests Partnership, and RMRS on this problem and we are well aware of the logistical and financial problems that prevented completion of the experiments. Prior to the next growing season, however, we strongly encourage all parties involved to focus on completing the burning. Second, we will be reporting separately on reconstruction of the historic fire regime in the study area. All field data has been collected and analysis is in progress.

The cooperative work of Grand Canyon Forests Partnership and the USDA Forest Service in the Flagstaff urban/wildland interface gained national attention during the severe 2000 fire season, when the "Flagstaff Plan" was much debated by proponents and opponents. We hope that the data presented here will prove useful in explaining the effects of initial experimental treatments and we look forward to continued collaboration with RMRS in following successional change in these treatment areas over time

EXPERIMENTAL FOREST TREATMENTS IN THE FLAGSTAFF URBAN/WILDLAND INTERFACE

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Introduction

This report describes the initial stages of an experiment to test forest treatments designed to restore natural ecological qualities and reduce the hazard to intense wildfires in the urban/wildland interface around Flagstaff, Arizona. We describe the pre-treatment conditions of the experimental blocks and the alteration in tree structure caused by thinning. Specifically, the report contains the following elements:

- Tree structure prior to the thinning treatment (composition, size distribution, biomass,snags),
- Tree structure after thinning,
- Tree biomass removed,
- Understory substrates before treatment (plants, litter, soil),
- Forest floor fuels before treatment.

Although treatments are still in progress, we prepared this report now to provide information to the Grand Canyon Forests Partnership about forest characteristics and the effects of thinning. Many important components of the research are not covered in the report, including: (1) reconstruction of presettlement forest structure and fire disturbance regime; (2) detailed understory composition and density; and (3) changes to fuels caused by addition of thinning slash. After fuel treatments and prescribed burning scheduled for completion by spring, 2001, the experimental blocks will be re-measured to determine the immediate post-treatment effects.

Background

In the urban/wildland interface of southwestern forests, the most urgent threat to human lives, houses and other developments, and the integrity of native ecosystems, is catastrophic destruction from high-intensity fire. Large-scale, intense wildfires are not a natural component of most southwestern forest ecosystems, but forests across western North America have undergone striking and deleterious changes since the introduction of land use practices such as heavy grazing of domestic livestock, harvesting of old-growth trees, and fire suppression, associated with Euro-American settlement in the late nineteenth century (Covington et al. 1994). Altered forest structure and function

has led to many critical conservation problems, including loss of native biological diversity, declining herbaceous and tree productivity, and high mortality of old-growth trees (Kolb et al. 1994, Biondi 1996, Mast et al. 1999). Presettlement forests were characterized by numerous fires of low intensity, a natural disturbance regime in the dry, seasonal southwestern climate (Swetnam and Baisan 1996). In the absence of fire over the past century, forests have become dense with small trees and forest floor fuels have accumulated. The new disturbance pattern of high-intensity, landscape-scale fires has begun in the Southwest and is evidenced most dramatically by the increasingly large, costly, and deadly wildfires in the 1990's. These fires kill old-growth trees, destroy the habitat of native plants and animals, and reduce future productivity through soil erosion (Foxx 1996, Rinne and Neary 1996, Campbell et al. 1977).

High-intensity wildfires can be especially devastating and costly when they occur in the interface between wildlands and communities. Urban/wildland interface fires threaten the lives, property, and habitats of residents. The high priority placed on suppression of interface fires means that other ecosystem values are often compromised when firefighters must abandon wildland fires in order to focus on the interface. The toll taken by fires in recent years in Boulder, CO, Oakland, CA, and Los Alamos, NM, underscore the need to address interface ecosystems in a comprehensive fashion.

The Grand Canyon Forests Partnership (GCFP) is a collaboration between the Coconino National Forest, Grand Canyon Forests Foundation, Northern Arizona University (NAU), and a number of other governmental and non-governmental organizations. The Partnership seeks to reduce the risk of catastrophic fire and restore forest ecosystem health through practices that are ecologically sound, economically viable, and socially acceptable. Returning more natural environmental conditions in northern Arizona, through restoring the forest structures and low-intensity fire regimes characteristic of the evolution of these ecosystems, is a promising approach to achieving the Partnership's goals. High-intensity crownfires cannot propagate in open, frequently burned forests. At the same time, studies in conservation biology and ecosystem health indicate that restoration of natural ecological structures and processes are most likely to improve ecosystem health and perpetuate native biological diversity.

Methods

Project development

The Grand Canyon Forests Partnership is a unique collaboration between the Forest Service and the Grand Canyon Forests Foundation, recognized as a National Reinvention Laboratory. The three primary goals of the GCFP are:

1. Restore the natural ecosystem functions--within the range of natural variability--of the ponderosa pine forests in Flagstaff's urban/wildland interface.
2. Manage forest fuels within the urban/wildland interface to reduce the risk of catastrophic fire.
3. Research, test, develop, and demonstrate key ecological, economic, and social dimensions of restoration efforts.

The NAU cooperators are participating in all aspects of the project, with representation as an official Partner in the GCFP and on the project management team. The special focus of the NAU cooperators, however, is in the ecological restoration and fire ecology components, as described below.

Ecological Restoration

Reversing the recent deleterious changes and restoring more nearly natural conditions—that is, conditions characteristic of the evolutionary environment of an ecosystem—is the basic concept of the science of restoration ecology (Society for Ecological Restoration 1993). The modern land management paradigm of ecosystem management is closely linked to ecological restoration, because it is based on the best possible understanding of the structure, function, and composition of intact, natural ecosystems as a point of reference for management strategies (Kaufmann et al. 1994). Wherever it is possible to maintain or restore evolutionary environments at large enough scales, the principles of conservation biology suggest that these habitats are most likely to perpetuate native plants and animals and allow their future evolution (Grumbine 1992). Many ecosystem changes which have already occurred are permanent (species extinction) or have long-lasting effects (loss of old-growth trees, atmospheric CO_2 increase). Restoration treatments cannot make up for these losses. However, the remaining majority of native species are still most likely to benefit from restoration of conditions as close as possible to natural. Substitutions can also occur: a new predator replacing the extirpated wolf, for example, or management fires replacing lightning ignitions. "Restoring" ecosystems encompasses a variety of possible treatments, ranging from restoring native ecosystem

components (for example, re-introducing an extirpated species or thinning trees to recreate an open forest structure) and natural processes (fires, floods) to removing exotic species which negatively affect natives. Finally, ecological restoration must be compatible with the goals and objectives of human society (Higgs 1997, Moore et al. 1999)

Specific restoration treatments and projected future conditions resulting from these treatments are outlined below:

- Ecosystem overstory structure: treatment in most cases requires removal of many dense, young trees, although in some circumstances tree planting may be necessary, such as after intense fires. The tree pattern prior to Euro-American settlement, evident in the living and dead trees of presettlement origin, is used as a template for reconstruction not only of presettlement density and species composition but also spatial pattern, restoring the clumpy structure of presettlement forests. Future forests are open and patchy, varying in density over the landscape just as the presettlement forest did. A series of alternative thinning prescriptions, varying in leave tree density, have been implemented in the initial experimental phase of the urban/wildland project. Three prescriptions were tested in controlled experiments, differing in residual tree density (see below). The differences between treatments are outlined graphically in Figure 1. An additional prescription, "minimal thinning," will also be applied in some areas outside the experimental blocks.
- Ecosystem dead biomass structure: treatment involves treating accumulated fuels to prevent unnatural fire effects (Sackett et al. 1996). In particular, presettlement trees surrounded by heavy forest floor material are protected from fire girdling by removal of excessive fuels two to four feet away from the trunk. Future forests contain low levels of woody fuels and litter, due to repeated burning. However, snags are also created by fire. Fire-injured "living snags" also provide snag habitat.
- Fire disturbance regimes: fire is re-introduced in prescription to the forest after overstory and fuel treatments are complete. Prescribed fires can emulate presettlement fire patterns for the first few burns, with an eventual goal of permitting large areas to burn from natural ignitions during the normal fire season. Because grass makes up most of the fuel in the future forest, the flaming front may move swiftly, but crownfires will not be possible in the open forest stands (although individual tree crowns may torch). Fires will burn frequently, but smoke production from the light fuels will be relatively low compared to present-day wildfires and prescribed burns.
- Ecosystem understory structure: shrubs and herbaceous plants respond rapidly when competing trees are thinned. However, the severely degraded conditions of many contemporary ecosystems

may require that livestock grazing, where permitted, be prevented for at least several years until the herbaceous community is well established. Transplanting and seeding with native species, controlling wildlife herbivory, and elimination of agressive exotics, may also be necessary in some cases to restore the understory. Future forests will contain diverse understories dominated by perennial native grasses and other native plants. Maintaining adequate herbaceous production to support periodic burning will be a key consideration in determining sustainable herbivory levels.

- Habitats: as vegetation structures and disturbance regimes are returned to conditions consistent with their evolutionary environment, habitats for insects, birds, other vertebrates, and humans will also change. In general, these changes should be favorable to the animals which evolved as part of the ponderosa pine ecosystem. For species dependent on forage, nectar, fruit, and seeds from diverse shrubs and herbs, such as many insects, small mammals, and birds, resources will increase. Species dependent on dense stands of postsettlement trees, such as bark beetles and squirrels, will lose resource biomass. While populations of individual species may rise or fall, the future forest will contain a variety of habitats which should collectively provide the most appropriate conditions to sustain native species.

Ecological restoration thinning prescriptions proposed for the urban/wildland interface project are based on retaining all living presettlement trees of all species and selecting younger replacement trees within a 60' search radius for dead presettlement trees, thereby emulating the density, species composition, and spatial pattern of the presettlement forest. Complete tree marking specifications are presented in Appendix B. Three thinning treatments differing in residual tree density were tested. The differences are due to different numbers of postsettlement trees selected to replace dead presettlement trees. The full restoration treatment involves replacement of a dead presettlement tree with **1.5** postsettlement trees, if the replacements are greater than 16" dbh, and **3** postsettlement trees, if the replacements are smaller than 16" dbh. The break at 16" is based on comparisons of replacement tree biomass and canopy. The alternate prescriptions are: **2-4 replacements**, substituting 2 trees for 1.5 and 4 for 3; and **3-6 replacements**, substituting 3 trees for 1.5 and 6 for 3.

Generalized differences in fuel model characteristics, tree competition, and understory productivity resulting from application of the different treatments to an example Fort Valley forest site are presented in Figure 1. The projected differences are not precisely quantified because the actual experimental blocks will vary from the example. The estimates in Figure 1 are only for general comparison; actual differences were quantified on experimental blocks following the methods outlined below. Fuel model assignments were determined from Anderson (1982). Tree competition estimates were generalized from Sutherland et al. (1991), Biondi (1996), and Covington et al. (1997).

Measurement and monitoring

1. Experimental design and study area

The alternative restoration treatments were tested on three experimental blocks (Figure 2) in or adjacent to the Fort Valley Experimental Forest. The study area has gentle topography and a cool, subhumid climate. Mean annual precipitation is 57 cm, with approximately half occurring as snow. The remainder occurs as summer monsoonal rains following the spring/early summer drought. Soils are of volcanic origin, a fine montmorillonitic complex of frigid Typic Argiboroll and Mollic Eutroboralf (Mast et al. 1999). The ponderosa pine structure consists of groups of mature trees, characterized by larger size and yellowed bark, above dense thickets of smaller, dark-barked trees. Understory vegetation includes perennial grasses, primarily Arizona fescue (*Festuca arizonica*), mountain muhly (*Muhlenbergia montana*), and squirreltail (*Sitanion hystrix*), and forbs. Experimental blocks were laid out in cooperation with Forest Service staff, subject to constraints of other experimental studies and wildlife habitat. Due to these constraints, the treatment units in experimental blocks 1 and 2 could not be contiguous. All treatments were randomly assigned.

2. Plot Measurements

Experimental block (EB) plot centers were established with tape and compass from surveyed reference points, such as section corners. Global positioning systems were used to geo-reference plots from each grid. Plot centers were permanently marked with rebar stakes and slope and aspect were recorded.

The suite of measurements and the EB plot design are adapted from: (1) the Fire Monitoring system developed by the National Park Service (Reeberg 1995); (2) sampling methods developed for measuring presettlement and contemporary ecosystem structure in southwestern forests (Fulé et al. 1997); and dendroecological sampling techniques (Covington and Moore 1994a).

Overstory trees over breast height (4.5 ft, 137 cm) were measured on a 400 m^2 (11.28 m radius) circular fixed-area plot. Species, condition, diameter at breast height (dbh), and a preliminary field classification of presettlement or postsettlement origin, were recorded for all live and dead trees over breast height, as well as for stumps and downed trees which surpassed breast height while alive. Tree condition classes were assigned based on a tree, snag and log classification system (Thomas et al. 1979) widely applied in ponderosa pine forests (Covington and Moore 1994b, Fulé et al. 1997). The nine condition classes (1-living, 2-declining, 3-recent snag, 4-loose bark snag, 5-clean snag, 6-snag broken above 1.37 m, 7-snag broken below 1.37 m, 8-downed, 9-cut stump) were used to determine dead tree structure and to estimate the death date of presettlement-era snags and logs, as described

below. Potentially presettlement ponderosa pine trees were identified based on size (dsh [diameter at stump height, 40 cm above ground level] > 40 cm) or yellowed bark (White 1985). Trees of all other species were considered as potentially presettlement if dsh > 40 cm, or dsh > 20 cm for oaks, pinyons, aspen and junipers. All potentially presettlement trees, as well as a random 10% subsample of other trees, were cored with an increment borer at 40 cm above ground level to determine age and past size, as described below. Diameter at stump height (dsh) was recorded for all cored trees. All overstory trees were marked with aluminum tags at breast height and tree locations were mapped.

Trees below breast height and shrubs were tallied by condition class and by three height classes (0-40 cm, 40.1-80 cm, and 80-137 cm) on a nested 100 m^2 (5.64 m radius) subplot. Shrubs over breast height were also measured. Herbaceous plants and canopy cover (vertical projection) are measured along a 50-m line transect oriented upslope with 25 m above and 25 m below the plot center. Point intercept measurements were recorded every 30 cm along the transect. Dead woody biomass and forest floor material were measured on a 50 ft planar transect in a random direction from each plot center. Photos were taken to plot center from 11.28 m N and E.

3. Laboratory procedures--Pre-treatment Forest Structure

Plot data were summarized by treatment units, each containing 20 permanent plots, and by experimental blocks. Forest overstory density, basal area, canopy cover, and diameter and age distributions were calculated. Tree biomass was calculated with allometric equations (W.W. Covington, unpublished data) and product volumes were calculated in cubic feet (trees < 9" dbh) and board feet (trees > 9" dbh) using equations developed by the Coconino National Forest from a northern Arizona mill study. Tree regeneration and shrub densities were calculated by species and height classes. Herbaceous transect data were used to determine the proportion of plant and non-plant intercepts, frequencies of native and non-native species, and species diversity and Simpson's Index (species diversity weighted by the number of individuals). Woody debris biomass was calculated using procedures in Brown (1974) and Sackett (1980). Forest floor depth measurements were converted to loading using equations from Ffolliott et al. (1976).

Results

Tree structure: pre-treatment

Tree composition was overwhelmingly dominated by ponderosa pine, making up 99.8% of all trees on the plots. Other species encountered included limber pine (*Pinus flexilis*), Gambel oak

(*Quercus gambelii*), Utah juniper (*Juniperus osteosperma*), and alligator juniper (*Juniperus deppeana*).

Experimental block 3, located outside the Fort Valley Experimental Forest, was different in many structural attributes from the other two blocks due to past management practices. In particular, block 3 had been more heavily harvested for large trees and had been thinned from below. As shown in Figure 3, the effect of these activities on the tree diameter distribution in block 3 was to remove both large and small trees from the site, leaving it dominated by mid-sized trees, especially in the 8-12" diameter class. In contrast, blocks 1 and 2 had more large trees but forest density was numerically dominated by trees in the smallest size class.

Average forest density prior to treatment was 538.1 trees/acre in block 1, 589.5 trees/acre in block 2, and 292 trees/acre in block 3 (Table 1A). The lower density in block 3 was due to previous thinning of small-diameter trees, especially those below 4" dbh (Figure 3). Although block 3 had the lowest pre-treatment tree density, however, it actually had the highest basal area (Table 2A). Average basal area ranged from a low of 146.7 ft^2/acre in block 1, to 162.8 ft^2/acre in block 2, to 164.5 ft^2/acre in block 3. Total tree biomass was nearly identical in all three experimental blocks prior to treatment (Table 3A), with an average of 117,341 lbs/acre in block 3, 117,495 lbs/acre in block 1, and 118,956 in block 2.

Canopy cover prior to treatment averaged 52.4% on block 1, 63.6% on block 2, and 67.0% on block 3.

Numerous small snags were encountered on all the experimental blocks (Table 4), but densities of large snags (16"+ dbh) were low: average of 1.5 snags/acre in block 1, 2.2 snags/acre in block 2, and only 0.5 snags/acre in block 3, where earlier harvesting had been most intense. Large dead and down logs (16"+ dbh) were also relatively sparse (Table 5), with an average of 1.6 logs/acre in block 1, 2.5 logs/acre in block 2, and 1.1 logs/acre in block 3.

Tree structure: post-treatment

The effects of thinning treatments on tree structure are *projected* in this section from the marked trees on the plots and field verification of thinning effects in the treated units. The thinning is still continuing in some of the experimental units. The data discussed here should therefore be viewed as preliminary. At this writing, several units still contain some small, non-commercial trees. For this analysis, we assumed that these trees will be thinned before burning.

Tree densities were reduced substantially in the thinned units (Table 1B). Residual tree density averaged 57 trees/acre in the full restoration treatment (range 37 to 74 trees/acre). The 2-4 treatment averaged 69 trees/acre (range 59 to 75 trees/acre). The 3-6 treatment averaged 98 trees/acre

(range 91 to 123 trees/acre). Post-treatment basal area values for full restoration (Table 2B) averaged 67.8 ft^2/acre (range 37 to 89 ft^2/acre), the 2-4 treatment averaged 77.8 ft^2/acre (range 48.8 to 102 ft^2/acre), and the 3-6 treatment averaged 97.1 ft^2/acre (range 91.6 to 104 ft^2/acre). Block 3 was consistently at the low end of the range in both residual tree density and basal area.

Diameter distributions of blocks 1 and 2, shown in Figure 3, reflected a major shift from dominance by small trees prior to treatment, to a more normally distributed diameter distribution following thinning. Because of earlier thinning in block 3, the reduction in density and alteration of the diameter distribution was much less pronounced. The ranges (minimum to maximum values) of diameter distributions in all three blocks were nearly unchanged by the treatment, because all of the largest trees were retained and at least a few small trees were retained in almost every unit.

The presence of large, old trees had a bigger effect on tree biomass changes than did the thinning prescriptions themselves. In blocks 1 and 2, within the Fort Valley Experimental Forest, a relatively high proportion of the total forest biomass was made up by presettlement trees (see Figure 3). Application of the thinning treatments, as summarized in Table 3B, therefore reduced tree biomass in these two blocks by proportions ranging from 17% (block 1, 3-6 treatment) to 36% (block 2, 1.5-2 treatment). Though experimental block 3 had a very similar total tree biomass prior to treatment, this block had a smaller proportion of large trees, so the reduction in tree biomass was proportionally larger. Tree biomass in block 3 was reduced 75% in the 1.5-3 treatment, 67% in the 2-4 treatment, and 32% in the 3-6 treatment. Following treatment, retained biomass ranged from 29,652 lbs/acre in block 3, 1.5-3 treatment, to 102,158 lbs/acre in block 1, 2-4 treatment. Product volumes (cubic feet and board feet) were calculated by Larson and Mirth (1999, report to Grand Canyon Forests Partnership.

In experimental block 3, some trees that were designated for retention under the marking prescription were removed after consultation with the sale administrator to accommodate landings or internal temporary roads (J. Gerritsma, personal communication). The additional volume removed in block 3 amounted to 2% of the board-foot volume in the full restoration treatment, 8.3% in the 2-4 treatment, and 2.6% in the 3-6 treatment. In experimental block 2, 8% of the board-foot volume in the 2-4 treatment unit was also cut from trees originally designated for retention.

Understory

Ground cover in the forest understory was primarily litter, making up from 60% to 68% by block of the material recorded along the point-intercept transects (Figure 4). Plants were the second most frequent substrate, comprising 14% to 24% of the cover. Other substrates included duff, rock, bare soil, and wood.

Fuels

Woody fuel loadings prior to treatment were highly variable, ranging from 5.5 to 26.6 tons/acre per unit (Table 6). The three experimental blocks were less variable, with average woody fuel loads of 16.7, 12.7, and 12.9 tons/acre in blocks 1, 2, and 3, respectively. Woody fuels are classified by fuel moisture timelag classes, which correspond to diameters as follows: 0-0.25" diameter = 1 hour timelag; 0.25-1" = 10 hour, 1-3" = 100 hour, and 3"+ = 1000 hour. The large woody fuels contributed most to loading and variability of fuels. The forest floor fuel load consisted of litter (freshly fallen leaves and other organic material) and duff (decomposing material). Litter ranged from 1.7 to 4.5 tons/acre and duff ranged from 5.1 to 11.7 tons/acre (Table 7).

Discussion

Tree structure

The three experimental blocks selected in the first phase of the Flagstaff Urban/Wildland Interface project are broadly representative of the Fort Valley 10K, including both lightly harvested (blocks 1 and 2) and heavily harvested (block 3) sites. In general, more individual trees were thinned in blocks 1 and 2 but more biomass was removed from block 3. Of the three thinning treatments tested, the full restoration treatment generally resulted in the most open and lowest biomass condition, while the 3-6 treatment retained the most dense forest and highest biomass, as expected. Results were fairly variable among individual treatment units, however, even those with the same thinning prescription. These differences reflect the underlying variability of the presettlement forest structure which served as the template for the thinning. Data on presettlement forest structure were collected on the experimental blocks but are not included here. When analysis is completed, we will compare the forest structure around 1876 to the post-treatment forest structure.

Densities of large snags and dead/downed coarse woody debris usually averaged less than 2 trees/acre. Under the treatment guidelines, snags of presettlement origin were to be conserved through the thinning and protected from burning by lining each tree.

To better represent the entire urban interface region, future experimental sites should also be located in the ponderosa pine—Gambel oak forest type to the SW of Flagstaff and on the cinder soils to the E where ponderosa pine mixes with pinyon pine and junipers.

Understory

Productivity and diversity of the herbaceous understory is limited in contemporary southwestern forests due to the high overstory density and deep forest floors (e.g., Covington and

Moore 1994b). However, we anticipate that the herbaceous community will respond positively to the thinning and burning treatments for two reasons. First, the community consists primarily of native species (data not shown pending completion of botanical analysis). Second, restoration treatments at the nearby Gus Pearson Natural Area led to a striking increase in herbaceous production within two years after thinning (Covington et al. 1997).

In addition to the permanent monitoring transects described here, NAU's Ecological Restoration Program is sponsoring three additional student research projects on the understory community in the experimental blocks: (1) treatment effects on productivity, seed bank, and mycorrhizal relationships (Julie Korb); (2) response of deerbrush (*Ceanothus fendleri*) to thinning and burning (Dave Huffman); and (3) mechanical logging effects on the forest floor (Brian Gideon).

Fuels and expected fire response

Fuel loadings on the experimental plots were consistent with fuels in similar forests across the Southwest (Sackett 1979). These fuels should not present undue difficulties for prescribed burning, except for the deep duff layers around old trees. The duff will be raked away from these trees before burning.

The slash that has been added to the fuel load in all the treatment units will be measured before burning. The degree to which the different harvesting methods influence slash production will also be assessed. Slash affects fire behavior and fire effects not only because the total quantity of fuel has increased, but also through qualitative differences in the fuel type. The elevated slash material, with drying ("red") pine needles, will ignite rapidly and support more intense fire behavior for a given weight of fuel, as compared to the more compacted litter on the forest floor. Fire behavior will be measured on the experimental blocks during the prescribed burning.

Fire danger, or the potential fire behavior on the site, has been altered in several ways by the treatment. Prior to treatment, fuel loads were moderate. The pre-treatment fuels could have burned in a surface fire, under relatively cool conditions, or could have supported fire spread into tree crowns under dry, windy conditions. The crownfire hazard was especially pronounced in blocks 1 and 2, where dense groups of small trees served as a fuel ladder to carry fire up to the overstory. After thinning and before burning, the surface fuel load has increased due to slash and the potential for intense surface fire behavior is even higher than before treatment. Although the ladder fuels are mostly gone, a wildfire in the slash fuels could cause damage to the residual overstory trees. After prescribed burning of the units, however, the majority of the hazardous fuels—the fine fuels that carry the flaming front and support intense burning—will be consumed. Larger logs and some duff material will probably remain on the units. At this point, fire hazard will be greatly reduced because both the

forest floor fuels and the canopy fuels will be at levels similar to those of the fire-resistant presettlement forest.

Repeated burning should maintain low forest floor fuel levels and prevent dense seedling patches from establishing. However, the treatment prescriptions all included a "buffer" of residual postsettlement trees above the density required to restore presettlement conditions. The excess was especially pronounced in the 2-4 and 3-6 treatments. Assuming that most of these retained trees grow well after thinning, tree canopies may begin to close in a few decades. Without future intervention to harvest the excess trees or create snags, the stands may again become capable of supporting torching and crownfire behavior, and gains in understory productivity may be reversed also.

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Table 1A. Tree density pre-treatment (trees/acre).

Block	Trt	0"-4"	4"-8"	8"-12"	12"-16"	16"-20"	20"-24"	24"-28"	28"-32"	32"-36"	36"-40"
1	Control	463.9	147.2	47.0	32.4	11.6	5.1	4.6	0.5		
1	Full	140.1	105.7	67.8	24.8	5.6	6.6	3.0	2.5	1.0	
1	2-4	568.6	156.8	36.9	21.2	9.1	9.6	4.0	4.0		
1	3-6	95.1	71.3	50.6	34.4	9.6	3.5	4.6	2.5		0.5
2	Control	191.2	98.1	79.9	54.6	12.1	2.5	1.5	2.5		
2	Full	259.0	97.1	58.7	36.9	15.7	4.6	2.0	0.5		
2	2-4	421.4	85.5	66.3	64.8	22.8	1.5		0.5		
2	3-6	469.5	172.0	79.4	42.0	12.1	3.0	0.5	0.5		
3	Control	31.9	75.4	89.5	71.3	15.2	3.0	0.5			
3	Full	23.3	96.1	147.2	51.1	8.6	1.0	1.0			
3	2-4	31.4	114.8	133.6	46.5	10.1	1.0	1.0			
3	3-6	26.3	46.5	69.8	49.6	19.7	3.0		0.5		

Table 1B. Tree density post-treatment (trees/acre).

Block	Trt	0"-4"	4"-8"	8"-12"	12"-16"	16"-20"	20"-24"	24"-28"	28"-32"	32"-36"	36"-40"
1	Control	463.9	147.2	47.0	32.4	11.6	5.1	4.6	0.5		
1	Full	3.5	7.6	26.3	17.7	5.6	6.6	3.0	2.5	1.0	
1	2-4	4.0	11.6	15.7	14.2	8.6	9.6	4.0	4.0		
1	3-6		5.6	26.8	27.8	9.1	3.5	4.6	2.5		0.5
2	Control	191.2	98.1	79.9	54.6	12.1	2.5	1.5	2.5		
2	Full	0.5	3.0	15.2	20.2	14.7	4.0	2.0	0.5		
2	2-4		3.5	21.2	32.4	16.2	1.5		0.5		
2	3-6	4.0	25.3	46.5	32.4	11.6	2.5	0.5	0.5		
3	Control	31.9	75.4	89.5	71.3	15.2	3.0	0.5			
3	Full		1.0	13.7	15.7	5.1	0.5	0.5			
3	2-4	0.5	6.1	26.3	19.7	5.1	1.0	0.5			
3	3-6	0.5	7.6	28.8	34.9	16.7	2.0		0.5		

Table 2A. Basal area pre-treatment (ft^2/acre).

Block	Trt	0"-4"	4"-8"	8"-12"	12"-16"	16"-20"	20"-24"	24"-28"	28"-32"	32"-36"	36"-40"
1	Control	12.5	25.3	25.1	33.6	19.0	13.1	16.8	2.3		
1	Full	4.6	19.8	36.3	25.2	9.0	16.5	11.2	11.3	6.0	
1	2-4	17.4	26.0	19.2	21.5	15.8	25.8	14.9	19.9		
1	3-6	3.3	12.9	28.1	36.9	15.4	9.5	16.3	12.7		3.7
2	Control	5.1	19.2	43.6	57.5	21.4	6.8	5.1	11.7		
2	Full	6.8	16.5	31.7	38.6	26.9	12.0	7.1	2.3		
2	2-4	8.8	16.3	37.2	69.3	38.6	3.5		2.3		
2	3-6	12.4	31.6	41.6	45.0	20.5	8.0	1.6	2.5		
3	Control	1.5	16.7	47.3	74.6	25.2	7.2	2.2			
3	Full	1.0	22.3	78.1	50.4	14.6	2.6	3.9			
3	2-4	1.0	27.1	69.1	46.3	17.2	2.5	3.5			
3	3-6	0.8	10.0	38.9	51.0	33.2	7.4		2.3		

Table 2B. Basal area post-treatment (ft^2/acre).

Block	Trt	0"-4"	4"-8"	8"-12"	12"-16"	16"-20"	20"-24"	24"-28"	28"-32"	32"-36"	36"-40"
1	Control	12.5	25.3	25.1	33.6	19.0	13.1	16.8	2.3		
1	Full	0.2	1.6	15.2	18.4	9.0	16.5	11.2	11.3	6.0	
1	2-4	0.1	2.8	8.2	15.0	15.1	25.8	14.9	19.9		
1	3-6		1.5	15.4	30.2	14.6	9.5	16.3	12.7		3.7
2	Control	5.1	19.2	43.6	57.5	21.4	6.8	5.1	11.7		
2	Full	0.04	0.8	9.1	21.9	25.2	10.6	7.1	2.3		
2	2-4		0.9	12.9	35.3	27.6	3.5		2.3		
2	3-6	0.1	5.6	24.9	35.2	19.4	6.5	1.6	2.5		
3	Control	1.5	16.7	47.3	74.6	25.2	7.2	2.2			
3	Full		0.3	8.3	16.3	8.8	1.3	1.9			
3	2-4		1.6	14.5	20.0	8.4	2.5	1.9			
3	3-6	0.02	1.8	16.9	37.2	28.4	5.0		2.3		

Table 3A. Tree biomass pre-treatment (lbs/acre).

Block	Trt	Total	Bark	Wood	Live Branch	Dead Branch	Foliage
1	Control	109,756	12,680	62,077	22,203	5,121	7,676
1	Full	112,802	12,480	65,117	22,931	4,960	7,313
1	2-4	129,616	14,183	75,127	26,287	5,648	8,370
1	3-6	117,806	12,702	68,793	24,030	4,995	7,286
2	Control	129,653	14,921	73,525	26,330	5,985	8,891
2	Full	106,881	12,346	60,493	21,690	4,962	7,390
2	2-4	128,493	15,165	71,986	26,060	6,125	9,156
2	3-6	110,798	13,536	60,960	22,306	5,555	8,442
3	Control	128,062	15,157	71,680	26,005	6,111	9,109
3	Full	118,622	14,566	65,161	23,968	5,949	8,977
3	2-4	113,622	13,992	62,307	22,940	5,723	8,649
3	3-6	109,059	12,653	61,638	22,197	5,067	7,503

Table 3B. Tree biomass post-treatment (lbs/acre).

Block	Trt	Total	Bark	Wood	Live Branch	Dead Branch	Foliage
1	Control	109,756	12,680	62,077	22,203	5,121	7,676
1	Full	84,869	8,632	50,779	17,415	3,317	4,726
1	2-4	102,158	10,104	61,787	21,004	3,843	5,420
1	3-6	97,926	10,020	58,454	20,090	3,857	5,504
2	Control	129,653	14,921	73,525	26,330	5,985	8,891
2	Full	68,313	7,275	40,125	14,014	2,829	4,070
2	2-4	67,417	7,520	38,816	13,793	2,965	4,324
2	3-6	74,850	8,545	42,629	15,256	3,404	5,016
3	Control	128,062	15,157	71,680	26,005	6,111	9,109
3	Full	29,652	3,341	16,994	6,059	1,323	1,936
3	2-4	37,451	4,329	21,207	7,629	1,730	2,556
3	3-6	74,181	8,319	42,603	15,164	3,288	4,807

Table 4. Snag density prior to treatment (trees/acre). Snags will be re-measured after treatment.

Block	Trt	0"-4"	4"-8"	8"-12"	12"-16"	16"-20"	20"-24"	24"-28"	28"-32"	32"-36"	36"-40"
1	Control	36.4	5.6	0.5	0.5		0.5	0.5	0.5		
1	Full	12.6	7.6	1.0				1.5			
1	2-4	52.1	5.6	0.5	0.5	0.5			0.5	0.5	
1	3-6	5.1	2.0	0.5	2.0		0.5	0.5	0.5		
2	Control	21.2	11.6	5.1	1.0		0.5	0.5		1.0	
2	Full	55.1	10.6	4.6	1.5	0.5	1.5	0.5			
2	2-4	35.4	10.1	2.5	0.5	0.5		1.0			
2	3-6	50.1	7.6	0.5	1.5	0.5	1.0	1.0			
3	Control	5.1	8.6	2.5	1.0	0.5	0.5				
3	Full	4.6	9.1	1.0							
3	2-4	3.0	15.2	2.0	1.5		0.5				
3	3-6	3.5	2.5			0.5					

Table 5. Density of dead and downed trees prior to treatment (trees/acre). Dead and downed trees will be re-measured after treatment.

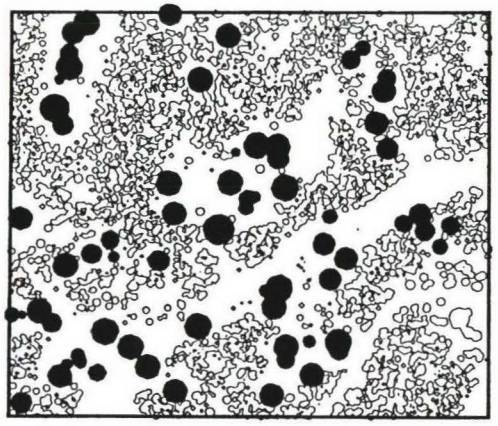
Block	Trt	0"-4"	4"-8"	8"-12"	12"-16"	16"-20"	20"-24"	24"-28"	28"-32"	32"-36"	36"-40"
1	Control	21.2	6.1		1.0	2.5		0.5			
1	Full	20.7	15.7	1.5	3.0	0.5	1.0				0.5
1	2-4	85.5	2.5	1.0	0.5					0.5	
1	3-6	7.6	1.5	0.5	1.0	0.5	0.5				
2	Control	42.0	14.2	2.5	0.5	1.0					
2	Full	64.2	15.7	2.5	2.0	1.5	2.0	1.5			
2	2-4	36.4	12.1	1.5	1.5					0.5	
2	3-6	28.3	6.6	2.0	2.0	2.0	0.5	1.0			
3	Control	4.6	8.1	1.5	0.5	0.5				0.5	
3	Full	6.1	7..1	0.5		0.5					
3	2-4	4.0	5.6	0.5	0.5	0.5				0.5	
3	3-6	3.5	3.0	1.5	0.5	1.0	0.5		0.5		

Table 6. Woody fuels pre-treatment (tons/acre). Slash fuels generated by the restoration thinning are not included.

Block	Trt	Total	1-Hour	10-Hour	100-Hour	1000-Hour (Sound)	1000-Hour (Rotten)
1	Control	26.6	0.1	0.7	1.7	6.2	10.9
1	Full	7.9	0.1	1.0	2.2	2.9	1.7
1	2-4	5.5	0.2	0.7	2.5	0.8	1.3
1	3-6	26.6	0.2	1.4	2.4	18.7	3.6
2	Control	14.5	0.1	0.8	1.8	3.7	0.1
2	Full	15.0	0.1	0.5	1.7	7.0	5.1
2	2-4	12.8	0.1	0.6	0.7	3.5	10.2
2	3-6	8.4	0.2	0.7	1.5	5.3	5.0
3	Control	9.7	0.1	0.9	1.9	4.3	1.2
3	Full	9.7	0.2	0.8	1.8	3.2	3.7
3	2-4	17.2	0.1	1.1	3.9	5.6	6.5
3	3-6	14.9	0.2	0.9	4.9	1.6	7.4

Table 7. Forest floor depth (inches) and loading (tons/acre).

Block	Trt	Litter(in)	Duff(in)	Litter Load	Duff Load
1	Control	0.3	1.2	2.4	9.6
1	Full	0.4	1.0	3.2	8.0
1	2-4	0.3	1.4	2.6	11.7
1	3-6	0.6	1.0	4.5	8.3
2	Control	0.3	1.4	2.5	11.4
2	Full	0.2	0.6	1.7	5.1
2	2-4	0.3	0.9	2.4	7.4
2	3-6	0.3	0.8	2.4	6.5
3	Control	0.3	1.1	2.7	9.2
3	Full	0.4	1.0	3.0	8.3
3	2-4	0.4	1.2	3.1	9.8
3	3-6	0.3	1.0	2.6	8.5



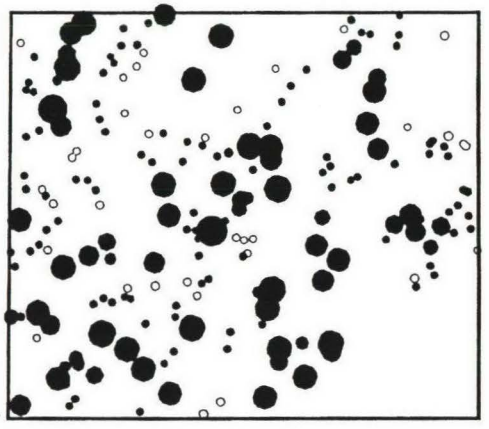
No-Action = CONTROL

Tree density:
1700 trees/acre

Fuel model: 9
Extensive ladder fuels
Height to crown ~ 6 ft.
Continuous crown fuels

Tree competition:
extremely high

Understory productivity:
very low



Intermediate (2-4)

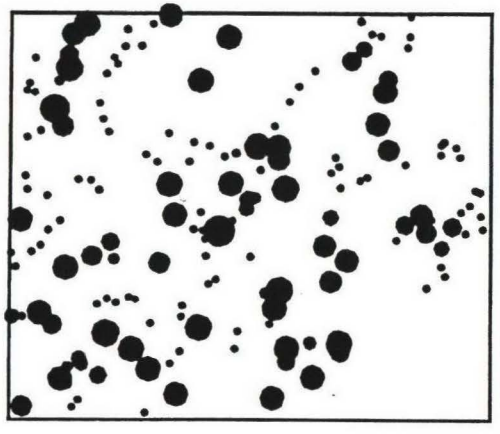
Tree density:
55 trees/acre

Fuel model: 2
Minimal ladder fuels
Height to crown ~ 30 ft.
Isolated crown fuels

Tree competition:
low

Understory productivity:
high

Full Restoration = 1.5-3 replacement trees

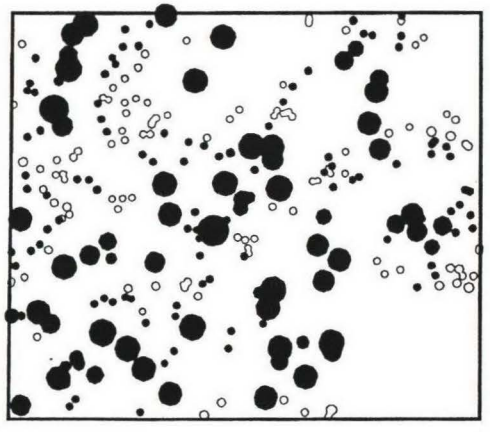


Tree density:
45 trees/acre

Fuel model: 2
No ladder fuels
Height to crown ~ 30 ft.
Isolated crown fuels

Tree competition:
low

Understory productivity:
very high



Intermediate (3-6)

Tree density:
76 trees/acre

Fuel model: 2 to 9
Some ladder fuels
Height to crown ~ 20 ft.
Some crown fuels

Tree competition:
moderate

Understory productivity:
moderate

Figure 1. Graphical comparison of ecological restoration treatments tested at the Fort Valley experimental blocks. The tree canopy from a 3.5-acre portion of the Fort Valley forest, stem-mapped in 1992 (Covington et al. 1997), was used as the "control" figure above. Treatments differing in retained tree density (noted as 1.5-3, 2-4, and 3-6 above) were applied and generalized differences in fuel models, tree competition, and understory productivity were estimated. In addition to tree thinning, all treatments except the control include fuel treatment, especially raking of accumulated forest floor material from the base of old-growth trees, followed by prescribed burning.

Fort Valley Study Site
Ponderosa Pine Ecosystem Restoration
Coconino National Forest

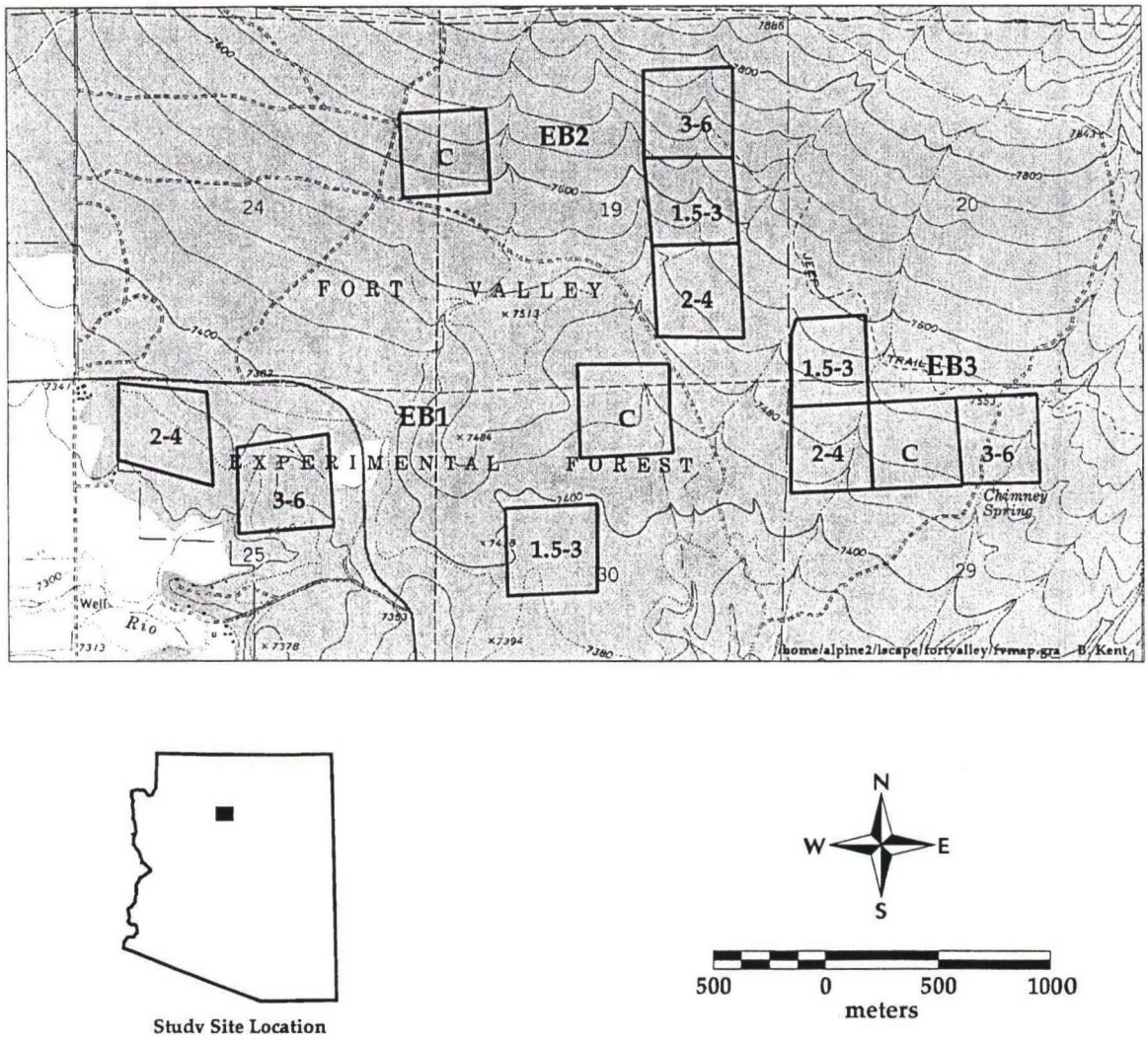


Figure 2. Location of the experimental blocks on the Fort Valley Experimental Forest/Coconino National Forest, Arizona. Treatment codes are shown in each unit as follows: C = control, 1.5-3 = full restoration thinning, and the 2-4 and 3-6 treatments are as described in the text.

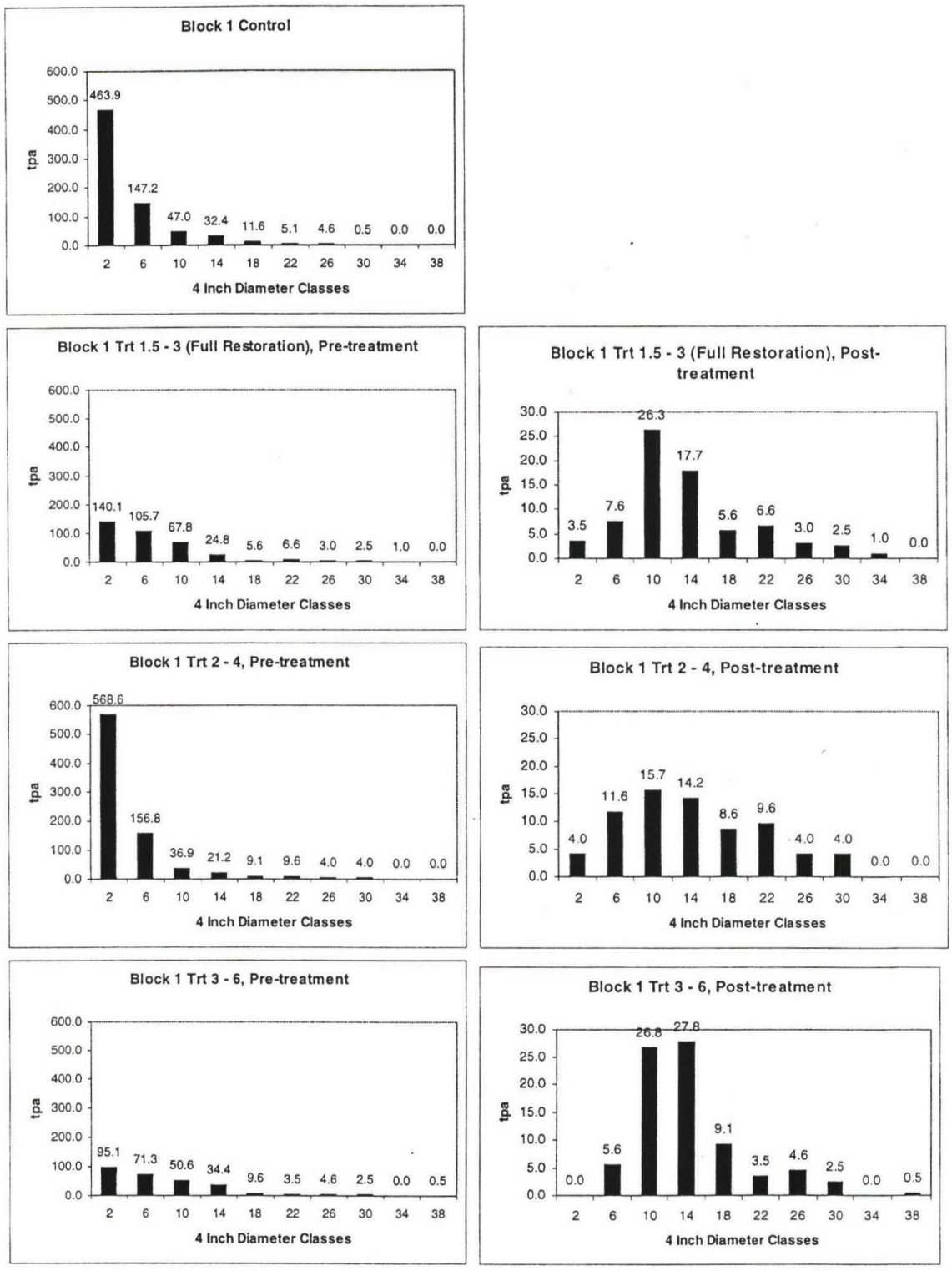


Figure 3. Diameter distributions in experimental block 1 before and after thinning treatments. The actual number of trees in each diameter class is printed above each bar.

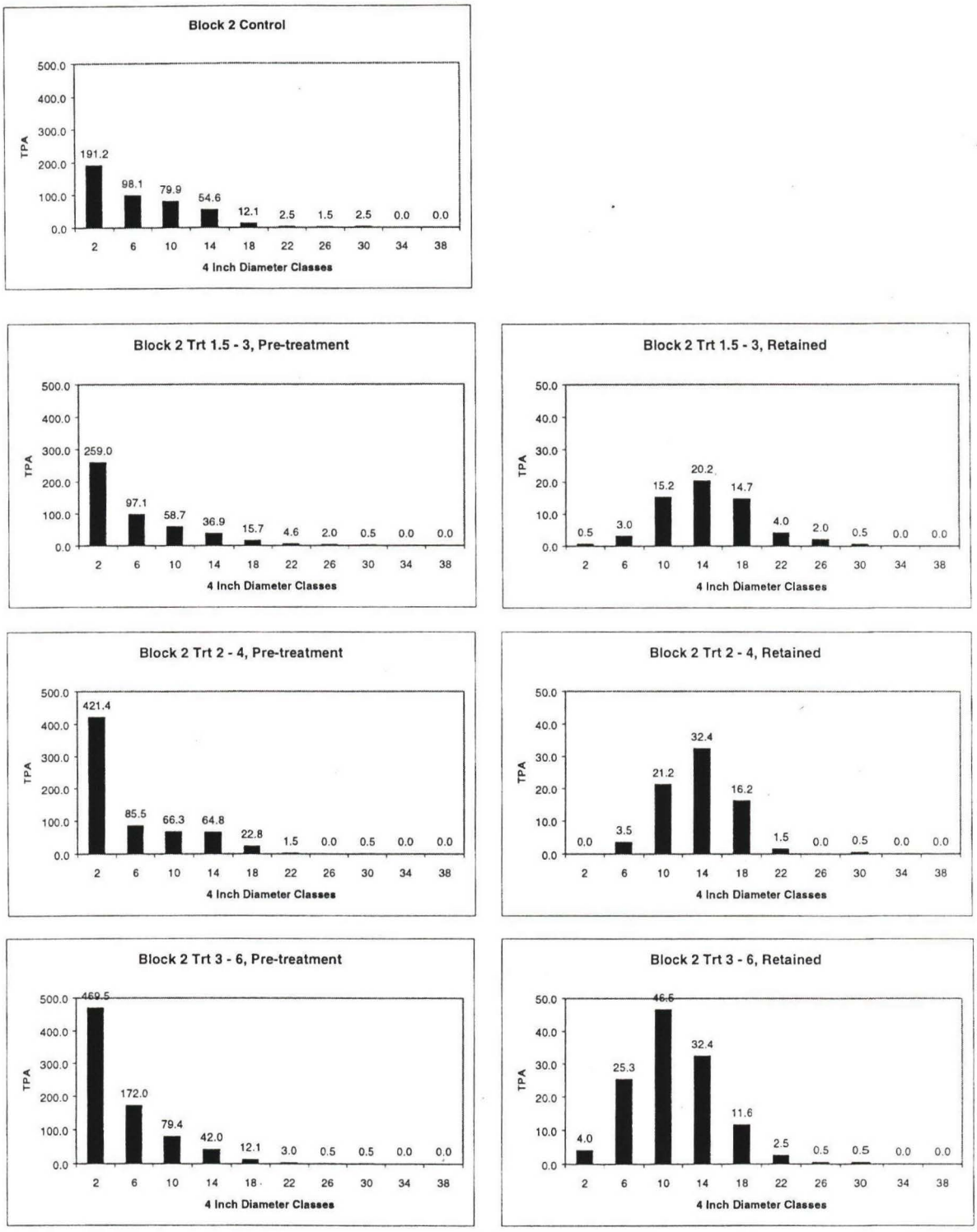
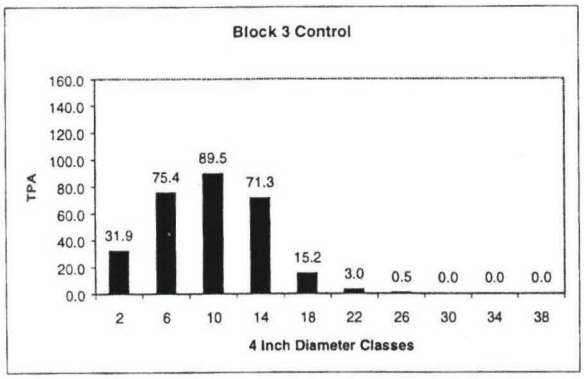
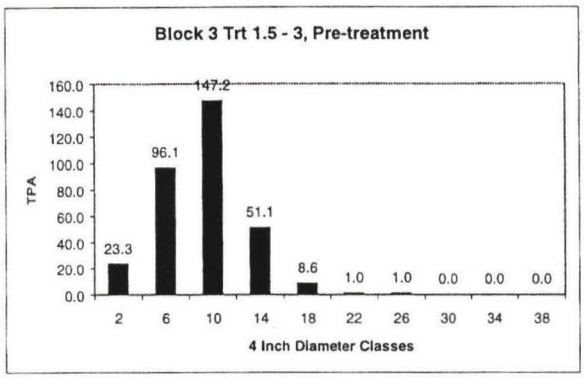
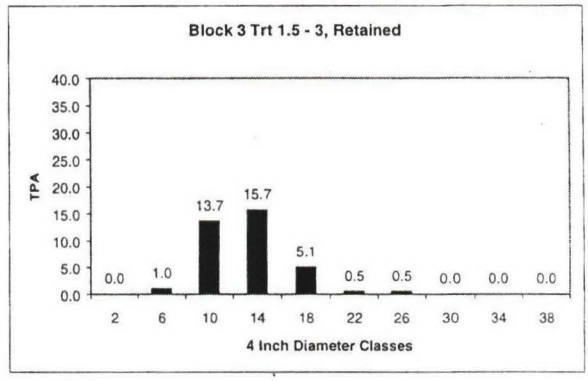
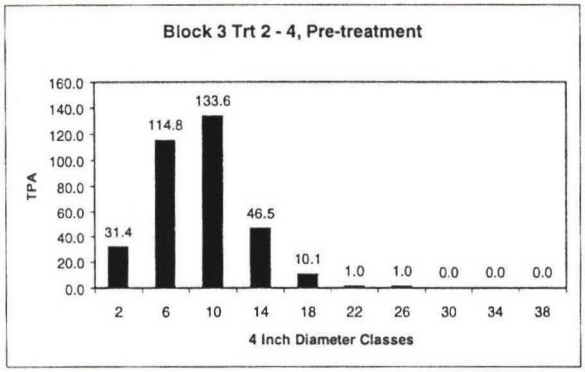


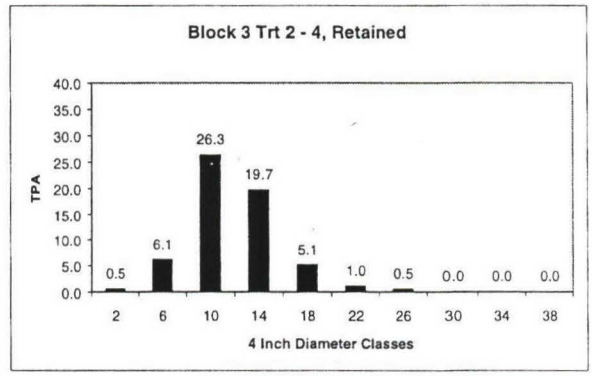
Figure 3 (continued). Diameter distributions in experimental block 2 before and after thinning treatments. The actual number of trees in each diameter class is printed above each bar.

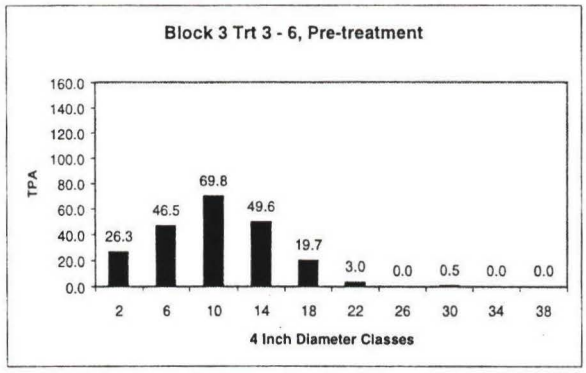












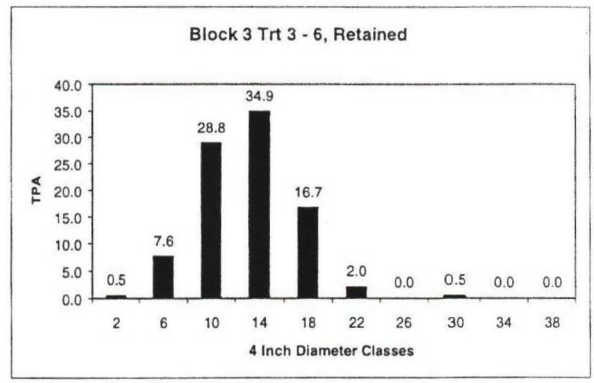


Figure 3 (continued). Diameter distributions in experimental block 3 before and after thinning treatments. The actual number of trees in each diameter class is printed above each bar.

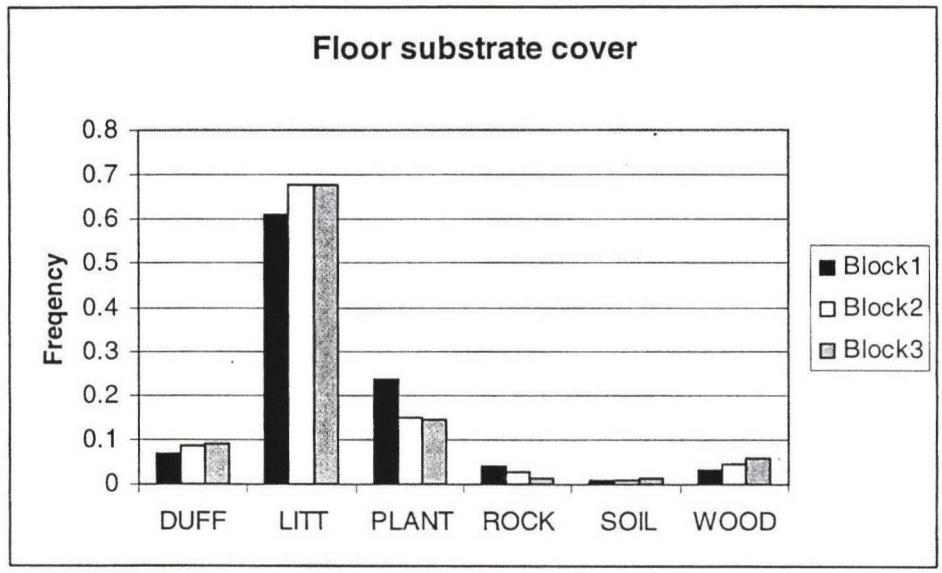


Figure 4. Herbaceous understory and forest floor substrates encountered along point-intercept transects. Litter (LITT) was the predominant substrate material found on the forest floor.

PART TWO:

POTENTIAL FIRE BEHAVIOR IS REDUCED FOLLOWING FOREST RESTORATION TREATMENTS

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Abstract

Potential fire behavior was compared under dry, windy weather conditions in 12 ponderosa pine stands treated with alternative thinning prescriptions in the wildland/urban interface of Flagstaff, Arizona. Prior to thinning, stands averaged 474 trees/acre, 158 ft^2/acre basal area, crown bulk density 0.0045 lb/ft^3, and crown base height 19.2 ft. Three thinning treatments differing in residual tree density were applied to each of 3 stands (total of 9 treated, 3 control). Treatments were based on historic forest structure prior to Euro-American settlement and disruption of the frequent fire regime (*circa* 1876). Thinning reduced stand densities 77-88%, basal areas 35-66%, crown bulk densities 24-48%, and raised crown base height an average of 11 ft. Before thinning, simulated fire behavior under the 97th percentile of June fire weather conditions was predicted to be intense but controllable (5.4 ft flame lengths). However, active or passive crownfires were simulated using crown base heights in the lowest quintile (20%) or winds gusting to 30 mph, representing the fuel ladders and wind gusts that are important for initiating crown burning. Under the identical conditions after thinning, all three treatments resisted crown burning. The degree of resistance was related to thinning intensity. It is crucial to remove thinning slash fuels through prescribed burning or other means. If not removed, slash fuels can cause crownfire behavior in the thinned stands under severe wildfire conditions. Finally, the crownfire resistance achieved through thinning will deteriorate over time unless maintenance burning and/or thinning is continued.

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INTRODUCTION

Flagstaff, Arizona, is located at the northwestern end of the largest contiguous ponderosa pine forest in the world. Increased fire intensity and severity are major concerns around Flagstaff and generally in southwestern ponderosa pine forests (Swetnam and Betancourt 1998), due to the regional increase in surface and canopy fuels following a century or more of fire exclusion and other human-caused disruptions of ecological processes (Cooper 1960, Covington et al. 1994). In 1996, the two largest wildfires in the history of the Coconino National Forest burned a few miles north of Flagstaff. Seeking to prevent such fires from burning into developed areas, a collaborative group called the Grand Canyon Forests Partnership was formed to restore ecosystem health, reduce catastrophic fires, and improve economic benefits and management on public lands (GCFP 1998).

Tree thinning, prescribed burning, and/or other fuel reduction methods can reduce the hazard of intense fires (e.g., Van Wagtendonk 1996, Graham et al. 1999, Agee et al. 2000). Using these techniques to restore a regime of frequent, low-intensity fires and tree structures approximating the relatively open presettlement forest stands should, in theory, simultaneously address the Partnership's goals. These treatments have potential for improving ecosystem health (Kolb et al. 1994), reducing fire hazard (Covington et al. 1997), and offering some economic benefits through forest product removal (Larson and Mirth 1998). Actually achieving this array of outcomes in complex ecosystems and social systems is difficult, requiring choices among competing interests. For example, Scott (1998a) compared the economic, aesthetic, ecological, and fire behavior tradeoffs of a set of alternative fuel treatments in a western Montana ponderosa pine forest. Kalabokidis and Omi (1998) carried out a similar analysis in a Colorado lodgepole pine forest.

The Grand Canyon Forests Partnership's initial wildland/urban interface experimental treatments was started in 1998 in cooperation with the Coconino National Forest and Rocky Mountain Research Station. The experiments had multiple objectives, but our focus in this paper is only on the treatment effects on potential fire behavior. The greatest concern in the wildland/urban interface is crownfire, both "passive" crownfire (tree torching) and "active" crownfire (fire spreading through the canopy). Crownfires spread rapidly (Rothermel 1991), resist control by hand crews and often mechanical or aerial equipment (Pyne et al. 1996), and threaten structures with intense heat and firebrand showers (Cohen 2000). Several complementary actions can improve the ability of communities to resist fire hazards to lives and property, including enhanced firefighting resources, improved access routes and rural address systems, heightened public awareness, reduction of structure flammability (Cohen 2000), and reduction of forest susceptibility to crownfire. The forest treatments

discussed here address the latter factor. Local initiatives are underway to enhance other fire-resistance factors in the Flagstaff wildland/urban interface.

Until recently, fire behavior modeling tools such as BEHAVE (Andrews 1986) simulated only surface fire behavior. New tools such as FARSITE (Finney 1998) and Nexus (Scott 1999) have greatly increased the ease with which many aspects of crownfire behavior can be modeled and compared. It is important not to attach too much specificity to crownfire behavior predictions: the fundamental reason that crownfire modeling has advanced slowly is that crownfires are rare and occur in extraordinarily complex weather and fuel environments (Rothermel 1991). With caveats, however, simulations provide useful insights into the relative differences between treatments and the relative sensitivity of crownfire behavior to different variables.

From previous simulations with FARSITE and Nexus, as well as from literature results (Van Wagtendonk 1996, Scott 1998a, 1998b), we recognized that simulations often resulted in outputs that appeared contrary to actual wildfire experience. In particular, simulated fires using our fuel and weather conditions proved nearly impossible to crown using realistic data, even though real fires had crowned under similar or even less severe conditions. One possible solution was to manipulate model output with adjustment factors. However, this method is unsatisfactory for modelers and their audiences, who would prefer to use well-supported numbers. We tried a different approach. Both with weather and fuel data, we reasoned that "average" conditions were a misrepresentation of the real forest situation. For instance, to cross the threshold into tree torching, surface flame lengths must preheat the branches and leaves close to the bottom of the crown. Achieving this transition in simulations has been difficult because the average crown base height is often a relatively high value (15-30 ft). The fuel ladders, surface fuel jackpots, and wind gusts that facilitate the transition to the crown in real fires are not accounted for when uniform averages are used.

Taking the variability of the data into account could help simulate more realistic fire behavior, but which fraction of the variability is important? A single low crown is probably insufficient to initiate a crownfire, but crownfires can start and be sustained in strong winds even with much less than 50% of the stand in a crownfire-susceptible condition. We chose to rank the data by quintiles—20% groups—and compare fire behavior and treatment effects on both the stand averages and the susceptible quintiles, suggesting that the fire behavior in the vulnerable quintiles may be important in triggering intense fires.

METHODS

Treatments

The Grand Canyon Forests Partnership chose to compare three treatments differing in residual tree density. All treatments were based on the presettlement pattern of tree structure as inferred from: (1) living trees of presettlement origin, characterized by larger size and yellowed bark (White 1985, Covington and Moore 1994), and (2) remnant material from snags, logs, and stumps of presettlement origin, which were well-conserved in the dry environment in the absence of fire (Dieterich 1980, Fulé et al. 1997, Covington et al. 1997, Mast et al. 1999). All living presettlement trees were retained. In addition, wherever evidence of remnant presettlement material was encountered, several of the largest postsettlement trees within 30' were retained as replacements. If suitable trees were not found within 30', the search radius was extended to 60'. The three thinning treatments each had a different replacement tree density:

- **1.5-3 replacements:** replace each remnant with 1.5 trees (i.e., 3 replacements per every 2 remnants) if the replacements were 16" dbh or larger, otherwise replace each remnant with 3 trees. Since relatively few >16" postsettlement trees were encountered in any of the sites, all the thinning treatments tended to retain the higher number of replacement. The 1.5-3 treatment, called "full restoration," reduced tree density most closely to presettlement levels.
- **2-4 replacements:** replace remnants with 2 trees > 16" dbh, otherwise 4 trees.
- **3-6 replacements:** replace remnants with 3 trees > 16" dbh, otherwise 6 trees.
- **Control treatment:** no thinning, no burning.

Study Sites

The treatments were tested on three experimental blocks in or adjacent to the Fort Valley Experimental Forest, approximately 15 km NW of Flagstaff, Arizona (Figure 1). Each block contained a 35-acre replicate of each of the three thinning levels and a control. The study area is at 7,400 ft elevation with gentle topography and a cool, subhumid climate (Avery et al. 1976). Mean annual precipitation is 57 cm, with approximately half occurring as snow. The remainder occurs as summer monsoonal rains following the spring/early summer drought. Soils are of volcanic origin, a fine montmorillonitic complex of frigid Typic Argiboroll and Mollic Eutroboralf (Mast et al. 1999). Experimental blocks were laid out in cooperation with Forest Service staff, subject to constraints of other experimental studies and wildlife habitat. As a result, the treatment units in experimental blocks 1 and 2 could not be contiguous. All treatments were randomly assigned.

The timing and method of treatment differed in the experimental blocks due to economic constraints, primarily the very low value of the material removed, and to the Partnership's intention to make the site available to different operators. Thinning of the blocks began in November, 1998, and was completed in September, 1999. Blocks 1 and 2 were thinned with a mechanical feller and limbed at the tree, resulting in broadcast slash fuels. Block 3 was thinned in a whole-tree harvesting operation, resulting in slash piles. Piles in block 3 were burned in February, 2000. All blocks were scheduled for broadcast burning in the spring or fall, 2000.

Measurements

Twenty experimental block (EB) plots were established on a 60-m grid in each of the 12 units. Plot centers were permanently marked with iron stakes at ground level and slope and aspect were recorded. Overstory trees over breast height (bh, 4.5 ft) were measured on a 0.1 acre (37 ft radius) circular fixed-area plot. Species, condition (1-living, 2-declining, 3-recent snag, 4-loose bark snag, 5-clean snag, 6-snag broken above bh, 7-snag broken below bh, 8-downed, 9-cut stump), and dbh, were recorded for all live and dead trees over breast height, as well as for stumps and downed trees which surpassed breast height while alive. Tree heights and average crown base height per plot were measured. Trees below breast height and shrubs were tallied by condition class and by three height classes (0-15.7 in., 15.8-31.5 in., and 31.6-54 in.) on a nested 0.025 acre (18.5 ft radius) subplot. Shrubs over breast height were also measured. Herbaceous plants and canopy cover (vertical projection) were measured along a 164-ft line transect oriented up- and down-slope. Point intercept measurements were recorded every 11.8 in. along each transect. Dead woody biomass and forest floor material were measured on a 50 ft planar transect in a random direction from each plot center. Fuels were measured by diameter/moisture timelag classes (1H timelag = 0–0.25 in. diameter, 10H = 0.25-1 in., 100 H = 1-3 in., 1000H = over 3 in., sound (S) and rotten (R) categories). Woody debris biomass was calculated using procedures in Brown (1974) and Sackett (1980). Forest floor depth measurements were converted to loading (Mg/ha) using equations from Ffolliott et al. (1976). Plots were originally measured from August through November, 1998. After thinning, pre-burn fuels were measured on the same transects in October, 1999.

Modeling

Fire behavior was modeled with the Nexus Fire Behavior and Hazard Assessment System (Scott and Reinhardt 1999). As described by Scott (1998a, 1999), Nexus integrates models of surface fire behavior (Rothermel 1972) with crown fire transition (Van Wagner 1977) and crown fire spread

(Rothermel 1991). Nexus is similar to the landscape fire behavior modeling program FARSITE (Finney 1998) in that both link the same set of surface and crownfire models. However, Nexus is better suited for comparing fire hazards under alternative conditions because environmental and fuel factors are kept constant for each simulation, rather than changing continuously with time and location, as in FARSITE.

Custom fire behavior fuel models were developed and tested with the NEWMDL and TSTMDL modules of BEHAVE (Andrews 1986). Pretreatment fuel models were modified from the standard fire behavior fuel model 9, "hardwood litter" (Anderson 1982). Post-thinning fuel models were modified from standard model 11, "light slash." Future fuels, after thinning and burning, are likely to have reduced woody fuel loads and increased herbaceous fuels. A hypothetical future fuel model was developed by modifying standard model 2, "timber (grass and understory)." The predicted future herbaceous fuel load was 200 lbs/acre, based on a basal area/herbaceous production relationship developed in northern Arizona (Brown et al. 1974).

Crown fuels were estimated with locally developed allometric equations for ponderosa pine shown in Table 1. Crown volume was estimated using averages of maximum tree height (top of the canopy) and crown base height (bottom of the canopy). Crown bulk density was calculated as crown biomass divided by crown volume. This procedure is straightforward and appears to adequately represent the canopy fuels actually available in a ponderosa pine crown fire. Alternative methods of crown fuel estimation can lead to substantially different numerical values, so density values in different studies may not be directly comparable. The situation is further complicated by the relatively high sensitivity of crownfire behavior modeling to canopy bulk density.

Fire weather extremes representing the 90^{th} and 97^{th} percentiles of low fuel moisture, high winds, and high temperature were calculated from 30 years of data on the Coconino National Forest using the FireFamily Plus program (Bradshaw and Brittain 1999). Weather values were calculated for the entire fire season (April 23 to October 16) as well as for June, historically the month with the most severe fire weather (Table 2). Fire behavior information from the two largest wildfires on the Coconino, the 1996 Horseshoe (May) and Hochderffer (June) fires, was used to estimate wind gusts during periods of extreme fire behavior (McCoy 1996). Wind gusts to 40 mph and sustained winds of 30 mph were observed on these fires. The thirty-year fire weather record also shows that winds of 30 or more mph were recorded in the 1300 hours observation on approximately 1% of June days.

RESULTS

Prior to treatment, forest structural conditions were similar across the study sites (Table 3). Basal area ranged from 148.5 to 167.7 ft^2/acre, while tree density was more variable (386.7 to 603.9

trees/acre). Average stand heights were within 7 ft of each other across the sites (67.2 to 73.9 ft) and average crown base heights were within approximately 4 ft (17.4 to 21.5 ft). Crown bulk density values averaged 0.064 to 0.083 kg/m^3, similar to values reported by Scott (1998a) in a Montana ponderosa forest. Thinning reduced tree density and biomass most strongly in the full restoration (1.5-3) treatment and least in the 3-6 treatment, as expected. Post-thinning densities ranged from 56.8 to 98.3 trees/acre, an average reduction of over 396 trees/acre (77% to 88% of trees removed). Since the largest trees were retained, however, basal area and crown biomass decreased by much smaller proportions. Post-thinning basal area ranged from 44% to 65% of pretreatment values. Thinning reduced crown bulk density to 52% to 76% of pretreatment values. Crown base height was raised an average of 11 ft and the lowest quintile (20%) of crown base height was raised an average of 10.6 ft from 8.5 ft before thinning to 19.1 ft after thinning. Pretreatment surface fuels averaged 25.4 tons/acre, but the quintile (20%) of plots with the heaviest loading of <1000H fuels averaged 38.2 tons/acre (Table 4). Post-thinning fuels were surprisingly similar between the broadcast slash blocks (11 tons/acre of <1000H fuels) and the whole-tree harvested block (7.2 tons/acre of <1000H fuels). However, the primary difference was an extra 3.9 tons/acre of 1H fuels in the broadcast blocks, the fuel component most strongly influencing fire behavior. The broadcast blocks did have 80% more heavy fuel (>1000H and duff) loading, 18 vs. 10 tons/acre. Burnout of these heavy fuels would be expected to lead to increased canopy and soil heating in the broadcast blocks after the passage of the flaming front.

Fires modeled in pretreatment conditions using the average stand values for crown bulk density and crown base height remained surface fires (Table 5) even under the severe fire weather conditions represented by the June 97th percentile (Table 2). Fire behavior outputs were virtually identical across treatments prior to treatment, with only slight differences in the torching index (an estimate of the windspeed required to initiate tree torching or "passive" crown fire behavior) and the crowning index (an estimate of the windspeed required to support "active" fire spreading through the crown). The minor fluctuations in these two indices reflected the small differences in crown base height (important for the transition from surface fire to torching) and canopy bulk density (important for sustaining active crownfire). The torching index showed that a wind of at least 45 mph would have been needed to cause passive crownfire. If fire were already in the crown or entered from outside the stand, a windspeed of 28-34 mph would have sufficed to sustain active canopy burning. However, both indices were above the modeled 25 mph windspeed. The simulated flame lengths, 5.4 ft, would have precluded direct attack by firefighters but mechanized equipment or indirect attack would have a high likelihood of successful suppression (Pyne et al. 1996). The fact that modeled fires were amenable to suppression even under severe wildfire conditions is an accurate reflection of reality: the

overwhelming majority of wildfires on the Coconino are contained below 10 acres (99.6%, fire records 1970-1999).

With 30 mph winds and/or the lowest quintile of crown base height, however, crownfire was simulated in the pretreatment sites. Keeping the crown base height at the average values but increasing wind to 30 mph led to conditional crownfire behavior (crownfire won't start, but could be sustained if it entered from outside the stand) in the stand with the highest crown bulk density. Lowering the crown base height to 8.5 ft, the average of the lowest pretreatment quintile, caused active or passive crownfire in all the sites at both the 25 and 30 mph windspeeds (Table 5). Since 30 mph or higher wind gusts occur, and since at least 1/5 of the modeled forest is vulnerable to crownfire, these results may bridge the apparent contradiction between observed crownfire behavior and the unrealistically high windspeeds required for simulated crownfires using average stand characteristics.

Thinning treatments substantially reduced fire behavior under the same environmental circumstances. As shown in Table 5, with the identical 30 mph wind and the lowest quintile of post-treatment crown base height, the simulated fire did not achieve any category of crown burning. All three treatments had the same torching index (49 mph) but the crowning index differed with canopy bulk density. The modeled 3-6 treatment could support conditional crownfire at windspeeds as low as 40 mph, while the modeled 1.5-3 treatment required 58 mph, 45% higher.

Although the comparison in Table 4 shows a clear change in fire behavior due to the restoration treatments, the post-thinning fuels are different than the pretreatment fuels. As the treatments progress, the slash fuels created by thinning are scheduled to be removed by prescribed burning. Mechanical means could also be used. But as long as these fuels remain in the stand, they present a threat of intense fire behavior. Active or passive fires crowned in all the simulated stands, including the treated sites, using either the broadcast or the whole-tree harvest slash fuel models in Table 4. With standard fuel model 11, however, the control had active crownfire but the treated stands had only surface fires.

Fire behavior in future fuels, after removal of the slash, will probably be influenced by a higher herbaceous component. Under the hypothetical model presented in Table 4, with 30 mph winds and the lowest quintile of crown base height, conditional crown fire was predicted for the control stands and surface fire for all the treated stands.

DISCUSSION

Model results should always be applied cautiously. Current models that link surface and crownfire behavior are highly sensitive to crown base height, windspeed (or wind reduction factor), fuel moisture, and surface fuel model variables (1H fuel loading, herbaceous fuels, surface-area-to-

volume ratio, fuel bed depth). We held slope constant at 7% (the average slope of the experimental blocks) but similar fuels on steeper slopes would exhibit higher fire intensity. There are a number of uncertainties in the models integrated in Nexus, reflecting the complexity of fire behavior (Scott 1998b). The actual numerical values used for model inputs produced realistic predictions but in some instances the differences between crown and surface fire behavior were separated by only a few miles/hr of windspeed (Table 5). If wind gusts of higher speeds or higher surface fuel loadings were encountered, portions of the stands would be more likely to exhibit crownfire behavior. The behavior of real fires in these stands would be affected by roads, meadows, surrounding forest fuels, landscape topography, and suppression activities.

The purpose of the modeling analysis was not to accurately estimate the behavior of a real fire but rather to compare the treatment alternatives. All three thinning treatments tested by the Grand Canyon Forests Partnership substantially reduced the potential for passive and active crownfire. All the treatments increased crown base height to nearly 30 ft, making passive crownfire initiation difficult. However, the different thinning levels in the three treatments created differences in crown bulk density that were reflected in the potential for active crownfire. Prior to treatment, the crowning indices of all the stands were separated by only 6 mph (top section of Table 5). After treatment (bottom of Table 5), the crowning index ranged from 28 mph (control stands), 40 mph (3-6 treatment), 47 mph (2-4 treatment), to 55 mph (1.5-3 treatment). In relative terms, taking the control crowning index as unity, the 3-6 treatment required 43% more windspeed, the 2-4 treatment required 68% more windspeed, and the 1.5-3 treatment required nearly double (96%) more windspeed, for active crownfire.

The restoration treatment is not complete when the thinning is finished. Slash fuels increase the fire hazard as long as they remain on the ground, so prompt treatment with prescribed fire or mechanical means is very important. Over time, vegetation in the treated units will change as both herbaceous plants and trees respond to the thinning. The potential intensity of grass-fueled fires should not be underestimated. Stand basal area even in the full restoration stands remained high enough to limit predicted herbaceous production to approximately 200 lbs/acre. If herbaceous production in the treated stands reached the 1000 lbs/acre in the standard fire behavior fuel model 2, passive crownfire was predicted in the lowest crown base quintile for all treatments under severe weather conditions. However, grass fuels would be unlikely to have reached full productivity or to be fully cured in June. Even with a high fireline intensity, grass fires are of short duration with few heavy fuels and are more amenable to control than timber fires. Strictly from a fire control perspective, therefore, a balance of relatively more trees and relatively less grass, such as the 2-4 or 3-6 treatments, might be useful in areas close to homes. On the other hand, future fire behavior will also

be influenced by the growth of residual trees and new regeneration. Treatments with relatively high residual density might more rapidly grow back into a hazardous condition. Maintenance burning and/or further thinning can be used to regulate growth and keep the stands relatively crownfire-resistant. The failure to carry out these management activities would eventually eliminate the original treatment effects on fire behavior.

Potential fire behavior is an important consideration in the design of wildland/urban interface forest treatments, but it is not the only consideration. Fire hazard tradeoffs should be recognized and evaluated against many other forest values. In the present analysis, we have incorporated some of the variability in fuels and weather. A more complete analysis, however, could include spatial variability within stands and across landscapes, temporal variability (diurnal to seasonal change), successional change (years to centuries), and predicted changes in land use. In addition to modeling intensity and behavior of the flaming front, the effects of fuel burnout and smoke production should be considered. Many of the tools and components of such a comprehensive analysis are being rapidly improved.

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Table 1. Allometric equations for ponderosa pine foliage and fine branches.

Variable	Equation	R^2
Total foliage	ln(biomass, kg) = -3.9274 + 1.9654 ln(dbh, cm)	.96
Needle-bearing twigs	ln(biomass, kg) = -4.5478 + 1.7352 ln(dbh, cm)	.85
0-0.63 cm branches	ln(biomass, kg) = -4.3268 + 1.4172 ln(dbh, cm)	.57

Table 2. Fuel moisture, wind, and temperature for the Coconino National Forest, 1970-1999. The 90th and 97th percentiles are shown for the entire fire season (April 23 to October 16) and for the month of June.

Variable	Fire Season 90th percentile	Fire Season 97th percentile	June 90th percentile	June 97th percentile
1 H moisture (%)	3.2	3.0	2.3	2.2
10 H moisture (%)	4.4	4.0	3.0	3.0
100 H moisture (%)	7.2	6.5	5.0	4.7
Wind speed (mph)	17.7	22.4	20.0	25
Temperature (°F)	82	82	89	89

Table 3. Forest stand structure and crown fuels at the Fort Valley study sites. See text for description of treatments. Prior to thinning, the lowest quintile of crown base heights averaged 8.5 feet. After thinning, the lowest quintile of crown base heights in the treated units averaged 19.1 feet.

	Control	Full Restoration (1.5-3)	Intermediate (2-4)	Intermediate (3-6)
		PRETREATMENT		
Basal area (ft^2/acre)	164.3	151.5	167.7	148.5
Trees/acre	480.6	386.7	603.9	422.3
Crown bulk density (lb/ft^3)	0.0052	0.0040	0.0044	0.0042
Average crown base height (ft)	21.5	19.1	17.4	18.9
Minimum crown base height (ft)	11.5	8.2	6.6	8.4
Crown fuel load (ton/acre)	5.2	4.8	5.3	4.6
Stand height (ft)	67.2	73.9	73.2	69.7
		POST-THINNING		
Basal area (ft^2/acre)	164.3	67.8	77.7	97.2
Trees/acre	480.6	56.8	68.8	98.3
Crown bulk density (lb/ft^3)	0.0052	0.0021	0.0026	0.0032
Average crown base height (ft)	21.5	29.1	31.9	27.4
Minimum crown base height (ft)	11.5	12.6	17.0	18.0
Crown fuel load (ton/acre)	5.2	2.0	2.3	2.9
Stand height (ft)	67.2	73.9	73.2	69.7

Table 4. Surface fuel characteristics. Fuels were measured on the study sites except for the "hypothetical post-treatment fuels" (see text).

Description	1 H (ton/ac)	10 H (ton/ac)	100 H (ton/ac)	Live (ton/ac)	SAV (1/ft)	SAVLive (1/ft)	Depth (ft)	Moist. Ext. (%)	Heat (BTU/lb)	1000 HS* (ton/ac)	1000 HR* (ton/ac)	Duff* (ton/ac)
Pretreat Average	2.9	0.8	2.3	0	2500	500	0.4	25	8000	5.9	4.8	8.7
Pretreat Top 20%	4.3	1.7	5.9	0	2500	500	0.5	25	8000	11.3	4.8	10.2
Post-thinning (broadcast slash)	7.2	1.2	2.6	0	1500	500	1.0	15	8000	7.1	3.9	7.0
Post-thinning (whole-tree harvest, piled slash)	3.3	1.2	2.7	0	1500	500	1.0	15	8000	2.2	0.8	7.0
Hypothetical post-treatment fuels: grass and understory, modified FBFM 2)	2.0	1.0	0.5	0.1	3000	1500	0.5	15	8000	N/A	N/A	N/A

* These variables are not included in fire behavior fuel models.

Table 5. Fire behavior outputs using the average pretreatment fuel loads under the June 97th percentile weather conditions with 97th percentile winds (top), 30-mph winds and lowest quintile crown base height (center), and posttreatment crown fuels with 30-mph winds and lowest posttreatment quintile crown base height (bottom). Foliar moisture content was held constant at 100%, wind reduction factor was 0.3, and slope was 7% (study site average) for all simulations.

	Control	Full Restoration (1.5-3)	Intermediate (2-4)	Intermediate (3-6)
	PRETREATMENT (June 97th percentile weather)			
Fire type	Surface	Surface	Surface	Surface
Crown percent burned	0	0	0	0
Rate of spread (ft/min)	28	28	28	28
Heat/area (BTU/ft^2)	491	491	491	491
Flame length (ft)	5.4	5.4	5.4	5.4
Crown Fire Outputs				
Torching index (mph)	54	49	45	48
Crowning index (mph)	28	34	32	33
	PRETREATMENT (June 97th percentile weather, 30-mph winds, lowest quintile crown base height)			
Fire type	Active	Passive	Passive	Passive
Crown percent burned	100	58	74	65
Rate of spread (ft/min)	128	90	105	97
Heat/area (BTU/ft^2)	2331	1473	1876	1569
Flame length (ft)	31.3	20.2	25.2	21.6
Crown Fire Outputs				
Torching index (mph)	23	23	23	23
Crowning index (mph)	28	34	32	33
	POSTTREATMENT (June 97th percentile weather, 30-mph winds, lowest quintile crown base height)			
Fire type	Active	Surface	Surface	Surface
Crown fraction burned	100	0	0	0
Rate of spread (ft/min)	128	37	37	37
Heat/area (BTU/ft^2)	2331	491	491	491
Flame length (ft)	31.3	6.2	6.2	6.2
Crown Fire Outputs				
Torching index (mph)	23	49	49	49
Crowning index (mph)	28	55	47	40

Figure 1. Post-thinning scene in one of the 3-6 treatment units with broadcast slash. Average and lowest quintile crown base heights were raised and crown bulk density was reduced by the thinning treatment, but slash treatment (burning, chipping, or removal) is necessary.